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# Design and Simulation of a 600 GHz RTD Oscillator using Commercial Harmonic Balance Software

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**Abstract** – We report on the design and optimisation of a 600 GHz double barrier resonant tunnelling diode (RTD) oscillator. Using the simple Esaki equivalent circuit diode model and published DC experimental I-V data, a custom device model was developed and integrated within a commercial harmonic balance (HB) simulator. This technique utilises a spline interpolation algorithm as part of the device model to determine instantaneous values of device voltage and current when called from within the main HB software. The maximum oscillation frequency for a  $5\ \Omega$  load was 1.6 THz, whilst optimisation at 600 GHz was achieved with a  $15\ \Omega$  load, with an output power of 420  $\mu$ W. The present technique should facilitate and simplify simulation of both existent and novel non-linear devices in other configurations, such as multipliers, mixers, self-oscillating mixers, etc.

## I. INTRODUCTION

During the past two decades, the RTD has been thoroughly investigated as a potential sub-millimetre wave source. To date, the best RTD oscillators were realised in the InGaAs/AlAs and InAs/AlSb material systems where the latter generated fundamental oscillations up to 712 GHz [1]. However, the highest reported power output of the RTD when used as a fundamental oscillator [2] still remained disappointingly low when compared to Schottky diode – based multipliers. Power combining was shown to bring about considerable improvement [3] while the series integration of RTDs [4,5] also seems promising. Yet, low power levels together with the inherent tendency for bias-circuit instabilities [6,7] have limited the use of RTDs in system applications.

Despite the current state of affairs, the RTD's potential as one of the fastest solid-state devices continues to attract interest in the scientific community. This is evidenced by a number of recent publications by various groups such as [4,5,8,9].

Novel oscillator designs based on device equivalent circuits are still being developed. To predict the performance of such oscillators, circuit simulations are necessary. Design techniques and analysis of RTD-based oscillators would benefit greatly from the implementation of commercial circuit simulators as this would speed up the optimisation process and also facilitate design and analysis of power combining schemes. In this type of work, a fundamental difficulty arises from incorporating essential non-linear current-voltage ( $I$ - $V$ ) and

capacitance-voltage ( $C$ - $V$ ) device characteristics using a satisfactory device model and making this compatible with the available CAD software. The following sections will describe the construction and validation of a user-defined model of a RTD followed by the design and optimisation of a 600 GHz RTD oscillator.

## II. MODEL CONSTRUCTION

Recent research activity in the development of large signal models of RTDs suitable for SPICE-type CAD tools has been significant. The early models employed simplified versions of the  $I$  –  $V$  characteristic such as piecewise linear [10] or polynomial [11,12] fits. Subsequently, more complex expressions were introduced [13-17] mainly due to the recent SPICE capability of representing transcendental forms of voltage-controlled current sources. These models range from a purely physics-based equation [13] to a totally empirical curve-fitting procedure [17].

Empirical curve-fitting to generate analytical expressions does not always reproduce real device behaviour accurately over the *entire* voltage-/current-/frequency-range of interest and entails the use of elaborate routines to generate a number of parameters, most of which would not be related to device physics. Likewise, physics-based models are generally insufficient to accurately reproduce experimental behaviour. It is therefore often found necessary to allow physical parameters to depart from their '*theoretical*' values to compensate for the necessary simplification of the model.

We believe that it is currently impossible to generate an analytic formula that faithfully reproduces device characteristics and that is easily adaptable from one device to another by simply specifying a number of RTD physical parameters. There are a number of reasons for this problem, but chiefly device characteristics change significantly even within small distances of the order of 1 mm on the same wafer. This is exacerbated by the fact that well-designed resonant tunnelling heterostructures exhibit strong negative differential resistance (NDR) effects in many material systems and over a wide range of current density [18]. The solution would be to characterise each actual device individually, if accuracy in system design and analysis is required.

The present technique was developed in order to circumvent these problems and is based on the use of device characteristics derived by cubic-spline interpolation of measured data. In contrast with piecewise-linear methods, cubic splines are continuous

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up to the second derivative and intrinsically smooth. Thus, most non-linear device characteristics may be represented faithfully with a number of data points not by far exceeding the number of parameters required for an equivalent representation in terms of analytic functions. In fact, only 16 data points were necessary to reproduce the experimental  $I$ - $V$  curve from Brown *et al.* [1], using a higher point density near the peak and valley to better reproduce the non-linearities. In the NDR region special care was taken to duplicate the maximum negative conductance of  $-64$  mS at about 1.3 V as reported in Ref. [1].

This model was developed within the context of Microwave Harmonica [19], which employs the HB algorithm developed by Rizzoli and his co-workers [20]. Specific FORTRAN code was developed to automate the process of constructing user defined models from external  $I$ - $V$  data files. The generated subroutine is then linked to the main commercial simulator. During analysis, the main program calls the subroutine, which determines instantaneous device voltage and current by spline interpolation. These are fed back to the main program for the successive iterations in the HB procedure. We have also generated a more complex model that allows for capacitance variation with device voltage based on data published in [21]. This will be reported elsewhere.

### III. MODEL VALIDATION

Figure 1 shows a simplified equivalent circuit of an oscillator with a RTD connected to a bias circuit and load. In the case of RTD oscillators, the active device provides the capacitance and negative differential conductance required. Therefore, the resonator only has to show inductive behaviour. As a first approximation, lumped element inductances  $L_B$  and  $L_R$  were assumed. The circuit of figure 1 was analysed using the commercial HB simulator. The parameters used were  $V_b = 1.35$  V,  $R_s = 3$   $\Omega$ ,  $C_d = 2.8$  fF,  $L_B = 1$   $\mu$ H,  $L_R = 25$  pH and  $R_L = 12$   $\Omega$ .  $R_s$  and  $C_d$  were obtained from data published in [1] while  $L_R$  was chosen to provide resonance conditions at 600 GHz. At this point no effort

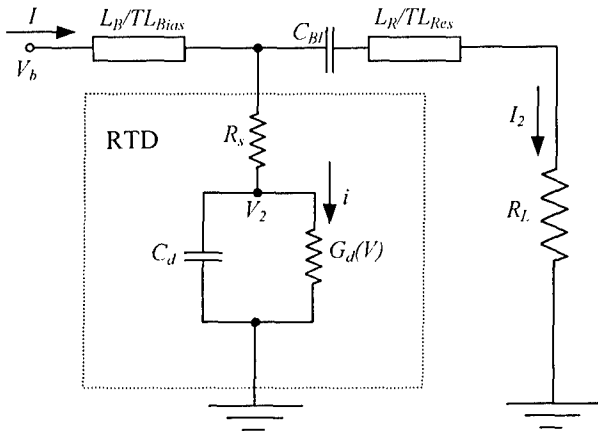


Fig. 1 : Equivalent circuit model of an RTD oscillator.  $L_B$  and  $L_R$  are lumped inductances used in model validation, whilst  $TL_{Bias}$  and  $TL_{Res}$  are transmission line lengths used in the 600 GHz oscillator design. Introduction of  $C_{BI}$  was necessary in the latter case.

was made to optimise the bias circuit and load. Basically, the aim of the exercise was to compare the output of the commercial simulator with the time domain solution. The output voltage waveforms across the load resistance  $R_L$  are shown in figure 2. These oscillations are nearly sinusoidal in nature and have a fundamental frequency of 530 GHz.

The time domain solution is obtained by solving a set of differential equations governing the behaviour of the circuit in figure 1:

$$\frac{dI}{dt} = \frac{V_b - IR_s + I_2 R_s - V_2}{L_B} \quad (1)$$

$$\frac{dI_2}{dt} = \frac{V_2 + IR_s - (R_s + R_L)I_2}{L_R} \quad (2)$$

$$\frac{dV_2}{dt} = \frac{I - i(V_2) - I_2}{C_d} \quad (3)$$

Equations (1) – (3) were solved using MATLAB [22]. Before the integration was carried out, the variable units were scaled to avoid numerical instabilities arising from small values of  $L_R$  and  $C_D$  in the denominator. To evaluate the right hand side of equation (3), the program used spline interpolation within the same data set as for the HB simulation. Figure 2 shows the time-domain voltage waveforms across the resistive load  $R_L$  compared to those obtained by the commercial simulator. Clearly, the two are in excellent agreement once the steady state is reached. Other simple circuits that demonstrate bistability, hysteresis and relaxation oscillations were also simulated successfully to confirm the validity of the RTD model within Harmonica. Section IV describes how this technique was employed in the optimum design of a 600 GHz oscillator.

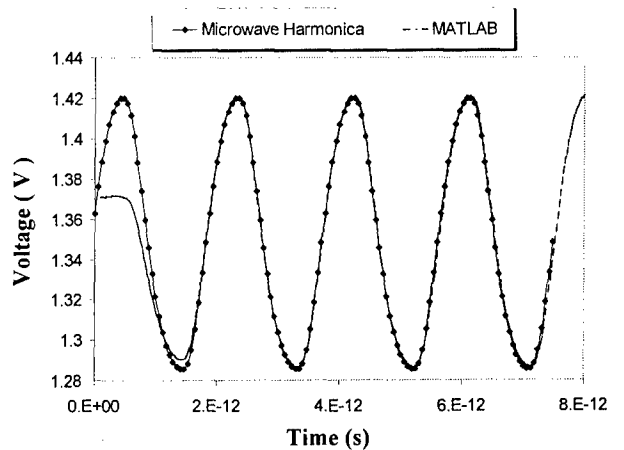


Fig. 2: Time domain voltage curves across load resistance  $R_L$ .

### IV. DESIGN OF A 600 GHz RTD-BASED OSCILLATOR

The oscillator shown in figure 1 employs the series resonance circuit technique where transmission line lengths  $TL_{Bias}$  and  $TL_{Res}$  are now used instead of  $L_B$  and  $L_R$  to fulfil the resonance requirement at the desired

frequency. The negative resistance of the RTD allows oscillations in the circuit while the blocking capacitor  $C_{BI}$  and the quarter wavelength transmission line  $TL_{Bias}$  constitute the biasing circuit. This topology follows Sigurdardóttir [8]. An optimum bias voltage of 1.4V was determined by a procedure similar to that described by Boric *et al* [12]. The other elements of the device model were a series resistance  $R_s = 3 \Omega$  and a device capacitance  $C_d = 2.8 \text{ fF}$  [1].

The output power and oscillation frequency depend on transmission line length and load resistance. This dependence was investigated for transmission line lengths varying from 20  $\mu\text{m}$  to 200  $\mu\text{m}$  and with two different loads of impedance 5  $\Omega$  and 20  $\Omega$ . The corresponding results are shown in figure 3. The maximum oscillation frequency was about 1.6 THz for the 5  $\Omega$  load, whilst with the 20  $\Omega$  load oscillations occurred only at frequencies below 550 GHz. This may be due to the transformation of the terminating impedance to capacitive at the device port, thereby annihilating the resonant circuit at a lower frequency. This general behaviour was also observed in [8] with similar orders of magnitude as regards oscillation frequency and power.

Finally, figure 3 suggests that the optimal transmission line length for a 600 GHz oscillator should lie between 70 and 90  $\mu\text{m}$ .

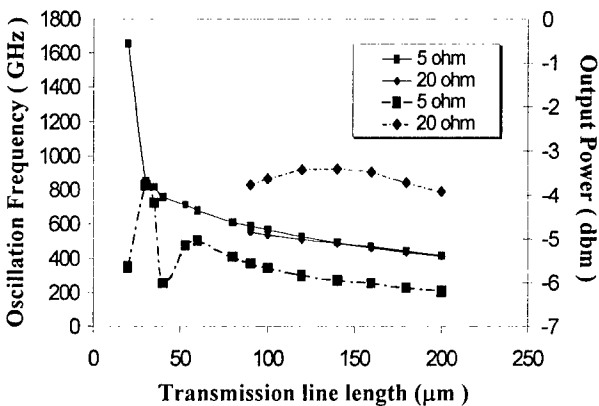


Fig. 3: Oscillation frequency (solid line) and output power (dashed line) as a function of transmission line length.

Figure 4 shows the available output power as a function of load resistance  $R_L$ .

The load resistance was varied from 2  $\Omega$  to 18  $\Omega$  while the transmission-line length was varied from 74  $\mu\text{m}$  to 86  $\mu\text{m}$ . It transpired that a load resistance of 15  $\Omega$  and a corresponding transmission line length of 78  $\mu\text{m}$  deliver the maximum power of 421.6  $\mu\text{W}$  at 600 GHz at a bias voltage of 1.4 V. This is much higher than the 0.3  $\mu\text{W}$  reported in [1] and would correspond to the absolute maximum power that can be delivered from that particular single InAs/AlSb RTD, assuming the simple Esaki diode model of fig. 1.

## V. CONCLUSION

This work was motivated in part by the need to model and optimise the behaviour of RTDs in the submillimetre

region, and by the usefulness of simple equivalent circuit models based on measurement data. We have reported a novel implementation of a spline interpolation algorithm within a commercial HB analysis package. To the best of the authors' knowledge, this is the first time that cubic spline interpolation of experimental data was incorporated into commercial HB software for the analysis of RTD-based microwave circuits. The technique reported here allows automated generation of custom device models and offers some attractive advantages over established analytic or semi-analytic

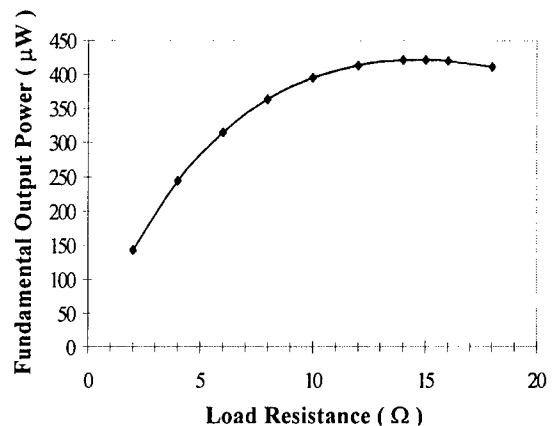


Fig. 4: Output power as a function of load resistance  $R_L$ .

techniques:

- virtually any device or device model may be incorporated into commercially available HB, or other non-linear analysis packages, providing the software allows definition of custom models, a feature which is becoming increasingly common;
- software implementation does not require construction of analytic functions with various parameters chosen to fit typical data. Instead, an *actual* device may be modelled, rather than a *typical* one, without the need of employing complicated curve fitting schemes.
- most non-linear device characteristics may be represented faithfully with a number of data points not by far exceeding the number of parameters required for an equivalent representation in terms of analytic functions. The computation time is not adversely effected since interpolation within a restricted set of data points is usually not significantly more computationally intensive than evaluating cumbersome analytic functions.

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